The Luminous Type Ic SN 1992ar at z=0.145

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ABSTRACT

We present spectroscopic and photometric observations of SN 1992ar, the more distant SN in the Calán/Tololo Survey. We compare its spectrum with those of nearby Type Ia and Ic SNe and conclude that the latter type is a better match to SN 1992ar. Using K–corrections based on the spectra of well observed Type Ic and Ia SNe we compute different possible rest frame light curves of SN 1992ar and compare them with those of representative SNe of each type observed in the nearby universe. From the photometry and the spectra, we are able to conclude that SN 1992ar cannot be matched by any known example of a Type Ia SN. Even though the data set collected is fairly complete (one spectrum and 10 photometric points), it is not possible to decide whether SN 1992ar was a fast Type Ic SN, like SN 1994I, or a slow one, like SN 1983V. The absolute V magnitudes at maximum implied by each of these possibilities are -19.2 and -20.2, respectively. The latter would make SN 1992ar one of the brightest SNe on record. SN 1992ar, hence, illustrates the problem of contamination faced by the high z Type Ia SNe samples whose luminosity distances are used to determine the cosmological parameters of the Universe. We present observational criteria to distinguish the two SN types when the SiIIλ6355 line is redshifted out of the sensitivity range of typical CCD detectors, and discuss the effect that these luminous Type Ic SNe would have on the measured cosmological parameters, if not removed from the High–z Type Ia SN samples.

Subject headings: (stars:) supernovae: general — (stars:) supernovae: individual (SN 1992ar) — (cosmology:) observations

1. Introduction

SN 1992ar is one of the supernovae (SNe) discovered by the Calán/Tololo collaboration (Hamuy et al. 1993). It was found by R. Antezana, on a plate taken with the CTIO Curtis–Schmidt telescope on UT 1992 July 27.23 (Hamuy & Maza 1992), close to a tight group of three anonymous galaxies (see Figure 1). The new object was confirmed as a SN 6 days later, through a spectrum taken with CTIO 4.0m telescope. Spectra of the nearby galaxies indicated that the group was at a redshift of $\sim$0.15, which made this the most distant SN discovered during the Calán/Tololo survey. Surprisingly, the spectrum of the SN revealed that the object more closely resembled a Type Ic event rather than a Type Ia. Preliminary calibration of a local sequence of standards and point spread function fitting photometry of the SN showed that SN 1992ar could be even brighter than a Type Ia SN, depending on K corrections which were unknown at the time. These brightness estimates were in strong contradiction with the expectation that Type Ib and Ic SNe (those formerly known as "Peculiar" Type Ia SNe) were subluminous with respect to Type Ia.

The belief that Type Ib and Ic were subluminous with respect to Type Ia SNe was rooted in both the observational record and theoretical interpretation. All SNe of these types, so far, had been 1.0–1.5 magnitudes dimmer than a typical Type Ia SN. The fact that they appear always associated with regions of very recent star formation suggested that they originated in stars of large main sequence mass which had lost the outer envelope and, hence, should explode through core collapse like Type II SNe. It is not yet clear what is the "typical" amount of ^{56}Ni that a core collapse explosion ejects. Although some events produced as much as $\sim$0.3 $M_\odot$ (Schmidt et al. 1994), comparative analysis of their late time light curves suggest that most of them eject between 0.04 and 0.10 $M_\odot$ (Patat et al. 1994). This, the successful interpretation and modeling of SN 1987A in terms of the ejection of 0.07 $M_\odot$ of ^{56}Ni (Woosley 1988; 1990), and the modeling of other Type II and stripped–envelope SNe in terms of explosions ejecting similar amounts of ^{56}Ni (Wheeler et al. 1993, Shigeyama et al. 1994, Woosley et al. 1994, Woosley et al. 1995, Clocchiatti et al. 1996a) strengthened the case for low ^{56}Ni production in typical core collapse SNe. The extreme brightness of SN 1992ar raises the question, therefore, of whether it might actually be a peculiar Type Ia event which just happens to bear a close spectroscopic resemblance with a SN Ic.

CCD observations at only three epochs were obtained from CTIO, the latest one 17 days after discovery. In addition, very late deep images of the field, when the SN brightness had faded beyond detection, were taken with the Blanco 4.0m telescope to allow subtraction of the galaxy background. Using this restricted database, Kohnenkamp (1995), did a preliminary study of this SN. Additional data, however, had been obtained at ESO, where researchers working under the Key Program on SNe followed SN 1992ar for more than 120 days after discovery. The CTIO and ESO data, when combined, provide a well sampled light curve with good signal-to-noise ratio, spanning nearly 105 days in the rest frame of the SN. These data permit a detailed comparison of SN 1992ar with typical Type Ia and Ib/c events. From this comparison, the nature of SN 1992ar can be finally established.

In Section 2 we present the spectrum of SN 1992ar. We describe the observations, reduction, and the spectrum itself, and compare it with spectra of nearby, well observed, Type Ia and Ic SNe. In Section 3 we describe the CCD photometric observations, the process used to eliminate the background light, and the calibration of the photometry in a standard system. Section 4 of this paper describes how we obtained a photographic magnitude from the discovery plate. Section 5 describes the K corrections we used to translate the observed photometry into the rest frame of the SN. In Section 6, finally, we reach the point where a light curve of SN 1992ar can be presented. In Section 7 we discuss our results and present our conclusions.

2. The spectrum

The confirming spectrum of SN 1992ar was obtained at the CTIO 4.0m Blanco telescope on UT 1992 August 2.34 by M. Hamuy and R. Williams. The Cassegrain Spectrograph and a 1240x400 Reticon CCD detector were used. The wavelength range covered was 3248–7500 Å, with a dispersion of 3.6 Å pix^{-1} (approximate resolution $\sim$7Å). Two exposures of 10 minutes each were obtained at an airmass of 1.07, approximately, bracketed by exposures of HeAr comparison lamps. Spectra of the three galaxies around the SN (see Fig. 1) and two flux standard stars of the list of Hamuy et al. (1994) were also obtained. All the objects were observed through a 2 arcsec slit, which was not oriented along the parallactic angle. The relative flux calibration of the spectrum is, hence, uncertain due to light loss by atmospheric dispersion. The absolute flux calibration is uncertain, as well, since the night was not photometric.

Image reduction and calibration followed the typical procedures. The spectrum images were divided by normalized flat–field images built from several exposures of the dome illuminated by two light sources with different spectral distribution to provide good signal-to-noise ratio in all the spectral range. Spectra of the SN were extracted and sky subtracted. Special care was taken in fitting the sky underneath the SN profile, since this SN appeared superimposed on a complicated background (See Fig. 1). The spectra were linearized in wavelength using the HeAr lamp exposures, corrected by atmospheric extinction using the mean extinction curve for CTIO, and calibrated in flux using the sensitivity curve for the night, obtained from the spectrophotometric standards. The two final SN spectra were normalized to the same mean value (multiplying the weakest by a constant), and, finally, combined. Spectra of the three neighboring galaxies were obtained and reduced in the same way.

The spectrum of the SN is plotted both in Figures 2, and 3, and the spectra of the neighboring galaxies are given in Figure 4. The redshifts for each galaxy, obtained from the average of several emission and/or absorption lines, are, 0.1452, 0.1450, and 0.1462, for galaxies A, B and C, respectively. They agree to within ± 360 km s^{-1}, confirming that the galaxies are physically associated. Note that narrow, weak [OII] $\lambda 3727$, Hβ, and [OIII] $\lambda 5007$ emission lines at z=0.146 are also present in the SN spectrum, pointing at a close association with the group.

Although it is not completely clear which of the galaxies was the actual host, circumstantial evidence suggests SN 1992ar was more closely related with galaxies A and/or B than with galaxy C. On the one hand, the projected positions of galaxies A and B are closer to the position of the SN than that of galaxy C. On the other, galaxies A and B show the strong emission lines characteristic of galaxies with starburst (Kennicutt, 1992), and Type Ic SNe are known to be strongly associated with massive star forming regions in nearby galaxies (Van Dyk, Hamuy & Filippenko, 1996).

Using the B & V transmission curves of Bessel (1990), we found that the color of the spectrum of SN 1992ar was B$-$V= 0.85. It is difficult to attach an error bar to this estimate. The relative spectrophotometry from CTIO spectra is typically outstanding (see for example Figure 2 in Phillips et al. 1992), with RMS uncertainty on the order of a few hundredths of a magnitude, similar to that of CCD photometry. We expect, however, that this would not be the case for SN 1992ar. One the one hand, this SN was dimmer than the examples available for comparison, and the background of the parent galaxies was more complicated than usual. On the other, our spectrum is not corrected for atmospheric dispersion. Although it is difficult to size the impact of the background on the spectrophotometry, an estimate of the atmospheric dispersion can be made. According to Table 1 of Filippenko (1982) the separation of the intensity peaks at the effective wavelengths of the B and V filters is smaller than 0.2 arcseconds (i.e., $<$10% of the slit width) if the airmass is ∼1.07. Assuming a Gaussian profile for the seeing and integrating the intensity profiles inside of the slit, this separation implies that the flux in B could have been reduced, at most, by 2% (i.e. our B−V color would be at most 0.02 mag too red). To be on the safe side, however, we assume an uncertainty of ±0.2 mag, about 5 times larger than the uncertainty in the photometry taken the day before, and 10 times larger than the expected systematic error due to atmospheric dispersion alone.

Finally, an estimate of the reddening from foreground interstellar matter can be made from the absence of NaI D lines. According to Burstein & Heiles (1984) the Galactic extinction in the direction of SN 1992ar is negligible. Regarding interstellar matter in the parent galaxy, the noise peaks in the region of the NaI D lines at the redshift of SN 1992ar imply an equivalent width smaller than ∼0.5 Å. In the absence of a better solution, this upper limit can be used to estimate an upper limit to the color excess. Clocchiatti et al. (1995) find that, in the case of SN 1993J, $E_{(B-V)}/EW = 0.21$ mag Å^{-1}, which would imply in the case of SN 1992ar a maximum E(B−V) of ∼0.1, or $A_{\mathrm{V,max}} \sim 0.3$ mag. We will neglect in what follows any correction for reddening. However, it should be kept in mind that our results could still be consistent with modest amounts of foreground extinction, up to a limit of ∼0.3 mag in V.

The spectrum of SN 1992ar is compared in Fig. 2 with spectra of the "normal" Type Ia SN 1989B and the peculiar Type Ia SN 1991T. The phases of the 1989B and 1991T spectra were chosen to be consistent with the phase implied for our spectrum of 1992ar (were it a SN Ia) by a spectroscopic matching technique (see §6.1). We can see that the similarities of the SN 1992ar spectrum with those of Type Ia SNe are, mainly, the broad features to the blue of ∼5300Å. These absorption features and P Cygni profiles are, from red to blue, due to FeII $\lambda5169$, FeII $\lambda5018$, FeII "$\lambda4555$", FeII "$\lambda4274$", and CaII H & K. Since they are present in the spectra of SNe of all types, including Type II, their potential to differentiate a SN from another is very limited. Features of CaII, FeII, and NaI, which are common to Type Ia and Ic SNe, and the SiII λ6355 line, which, although weaker than in Type Ia, also appears in Type Ic SNe, are labeled with lower case letters.

Even though the similarities in this spectral region are clear, there are a few differences worth noting. The features of SN 1992ar are shallower and broader, and the spectra of Type Ia SNe show narrow cores in the absorption lines. These differences are particularly noticeable between 3900 and 4200 Å, and between 4700 and 5100 Å. In the former region, the main difference is made by the feature labeled with letter A, which corresponds to SiII λ4130. In the latter region, there is an additional feature, labeled with letter B, which corresponds to SiII λ5051.

It is, however, in the region to the red of $\sim$5200 Å that the distinct character of the spectrum of SN 1992ar becomes clear. First, the strong SiII λ6355 line, centered between 6100 and 6200 Å in SN 1989B and 1991T, is absent in SN 1992ar. Second, the much weaker but also distinctly present absorption centered near 5500Å in the Type Ia SNe, typically attributed to SII λ5612 and SII λ5654 (labeled with letter D in the figure), is also absent. There is another, much weaker, feature about 200 Å to the blue, labeled with letter C in the figure, which corresponds to SII λ5468. The signal-to-noise ratio of the spectrum of SN 1992ar is not good enough to decide whether this small feature is present or not.

Strong SiII lines and clearly detectable SII lines are characteristic features of Type Ia SNe. The fact that SN 1992ar does not show them is a clear indication that, if it were a Type Ia SN, it would be even more spectroscopically peculiar than SN 1991T.

Consistent with this, Fig. 3 shows that there are no major differences between the spectra of typical Type Ic SNe 1983V or 1987M and that of SN 1992ar. With the exception of the CaII H & K lines, the spectrum of SN 1983V is remarkably similar to that of SN 1992ar. However, since Type Ic SNe do show differences in the strength of the CaII lines, the weaker spectral features are not a major concern. Paradoxically, one of the notable differences in this figure is, again, the SiII $\lambda6355$ line. Although it is clear that the spectra shown Fig. 3 are type Ic, one sees that this line was stronger in SN 1987M than in the other two.

3. CCD Photometry

We have collected 10 CCD images of SN 1992ar taken from telescopes at CTIO and ESO. A description of the dates, telescopes used, observers, and other relevant information is given in Table 1. The images, taken through standard Johnson B, V (Johnson 1955), and Cousins R (Cousins 1976a, 1976b, 1978) filters were reduced following standard procedures. The CCD pedestal was corrected using its overscan region, any remainder 2-dimensional pattern was removed using bias images when necessary. No correction for dark current was required. Finally, pixel to pixel sensitivity variations were removed using median dome or sky flat field images.

SN 1992ar appeared on a complicated background (see Fig. 1). The nearby galaxies 1 and 2 mean that the sky near the SN is bright and has a large gradient. In addition, the SN is centered on a valley of the brightness distribution. This configuration makes both aperture and PSF fitting photometry bad prospects.

In order to do unbiased photometry, we resorted to eliminating the light of the nearby galaxies by taking very late-epoch images of the region, with good signal-to-noise ratio. Information on these images, which we refer to in what follows as the final epoch images, is given in Table 2. We used the image matching algorithms described by Phillips & Davis (1995), proceeding in detail as follows: (a) We shifted and rotated the final epoch image so that the centers of the stars were in coincidence with those of the image with the SN;

(b) we found the difference kernel that, when convolved with the image of the narrowest PSF (usually this is the final epoch image), would degrade it to match the PSF of the other image, and convolved the image with better seeing with that kernel; (c) we found the linear transformation in intensities to make the final epoch image match the intensities of the image with the SN, and applied that transformation to the final epoch image; (e) we subtracted the region around the SN of the transformed final epoch image from the image with the SN. After this procedure we found that the background of the galaxies near the SN had been removed, and that the sky underneath the SN was flat.

We did relative photometry of the SN on the images with the background subtracted. Using the tasks of the package DAOPHOT in IRAF[29] we built a mean PSF for each frame from the profiles of the stars in the field and found the instrumental magnitudes of the local sequence of standards and the SN by fitting this PSF function.

The sequence of local standard stars indicated in Fig. 1 was calibrated in Johnson B and V colors using observations taken with CTIO 0.9m telescope on August 22, 1993. On that night, images of the region of SN 1992ar were taken together with standard stars of the lists of Graham (1982), Menzies et al. (1989), and Landolt (1992). The zero points, extinction coefficients, and color terms were fitted to find the photometric solution for the night, and the B and V magnitudes given in Table 3 were computed from this solution.

We did not have a photometric night with enough standard star observations to compute all the coefficients in the photometric solution for the Cousins R filter. The final epoch image, however, was taken on a photometric night and our set of images

[29]The Image Reduction and Analysis Facility (IRAF) is maintained and distributed by the Association of Universities for Research in Astronomy Inc., under a cooperative agreement with the National Science Foundation.

included three standard stars of the list of Landolt (1992). We used these stars, a mean extinction coefficient for La Silla from the database of the Photometry Group of the Geneva Observatory (Burki et al. 1995), and a typical color term for the instrument used (Turatto, 1996), to find the zero point of the calibration in R. Due to the characteristics of this solution, there could be a systematic error in the calibrated R magnitude for the local sequence of standards. It must be small, however, of the order of the uncertainties given in Table 1, since the two color diagram of the local standard sequence looks reasonable. We decided to give the R values out of completeness. In the event that these particular observations of SN 1992ar become important (to estimate the foreground extinction by comparing the late time V-R color with those of future Type Ic SNe, for example) the sequence can be recalibrated and a correction to the values given in Table 1 could be computed.

Using the instrumental magnitudes of the stars in the frames with the SN and their B, V, and R magnitudes, we computed a zero point for each frame and applied it to the instrumental magnitude of the SN. The color terms for all the combinations of CCD and instruments used is small, so color term corrections to the magnitude of the SN relative to the local standard stars are expected to be smaller than the photometric uncertainty. Consistent with this, we found the zero points to be independent of the color of the local sequence stars. The magnitudes of the SN, calibrated in this way, are given in Table 1.

4. Photographic Photometry

As it will become clear in the next section, to find the nature of SN 1992ar requires us to use all possible data at hand, including its discovery plate. A complication in this regard is that the search plates of the Calán/Tololo survey were taken without a filter. However, the standard Kodak IIa0 emulsion, with a red cut–off very similar to that of the Johnson

B band, was employed. This, together with the fairly red color of SN 1992ar, suggest that it should be possible to get a good estimate of its B magnitude from the photographic magnitude.

There were three Schmidt plates in the database of Cerro Calán Observatory with images of the region of SN 1992ar (Wischnjewsky 1997). One of them is the first epoch image, which was taken on June 26.5 1992, the second is the discovery image, taken on July 27.3 1992, the third is an additional plate taken on August 2.5 1992. Ideally, these plates could have been used to digitize the region of the SN and sequence of local photometric standards in all the plates, transform the photographic density to an approximate intensity scale, use the plate of June 26.5 to estimate the background underneath the SN and subtract it from the other two plates, compute magnitudes for the local standards and the SN, analyze the correlation between the instrumental photographic magnitudes and the calibrated magnitudes for the standard stars in all plates, and use this correlation to estimate the photographic magnitude of the SN in a standard passband. Since by August 2.5 the light curve is known from CCD observations, the calibration of the August plate would be useful to check the accuracy of the photographic photometry.

We were able to accomplish this project only partially. On the one hand, we found that the photographic density of the sky in the region of the SN was only marginally detectable in the June image (negative observation) and, hence, dominated by noise. This made it useless to model the background of the SN. In addition, the seeing of the plate of August 2.5 was worse than that of the discovery plate. Since the SN was fainter on August 2.5 than on July 27.3, the plate of August provides only a marginal detection of the SN, not good enough to set a meaningful constraint on the precision of the photographic photometry.

We decided, then, to use our final epoch CCD images to model the background of the SN in the digitized discovery plate, and desist in our desire to check the accuracy of the photographic photometry. We proceeded as follows. Building upon the suggestions of Stetson (1979), especially his equations 9–11 we took the photographic density to be proportional to the intensity, an approximation which holds true in the limit of stellar images of low intensity above the background. We transformed our final epoch CCD images in the B filter to the pixel scale of the plate, studied the correlation (pixel by pixel) of the intensity recorded by the CCD and the photographic density in regions of low density, and found that they were actually consistent with a linear transformation. We found the linear transformation that best fit the correlation, and applied it to the CCD image. We then took a small region of the transformed CCD image, centered on the SN position, and subtracted the transformed CCD intensity distribution of this region from the photographic density. We found that the sky around the SN was acceptably well subtracted, leaving residuals only near the cores of the nearby galaxies (where the assumption of CCD intensity proportional to photographic density was expected to break down).

We used this final image to compute the photographic index of the local standard sequence and SN. We did not have enough stars to model the photographic PSF shape and correct for saturation at high photographic density (as in Stetson, 1979). We resorted, therefore, to computing our photographic index using aperture photometry. Using 7 stars imaged both in the CCD and the plate, we found a tight linear correlation between our photographic index and the B magnitude of the stars in the local sequence. The scatter of the correlation, which spans 2.6 magnitudes in the photographic index, is 0.05 mag. The residuals of the fit, in addition, display a small but statistically significant color term. From the correlation and color term obtained, the B magnitude of SN 1992ar on the discovery plate is given by,

$$\mathrm{B} = 20.70 \pm 0.17 - (0.183 \pm 0.032)\,(\mathrm{B} - \mathrm{V}) \tag{1}$$

The color term in this equation is the same, within the uncertainty, as those found by Pierce & Jacoby (1995) and Arp (1961), in transforming magnitudes from IIaO plates to B.

The uncertainty given in equation 1 results from combining in quadrature the uncertainty in the instrumental magnitude of the SN and the RMS of the transformation of the stars in the local sequence. There is an additional uncertainty, that we cannot evaluate, because the SN is fainter than the faintest star in the local sequence of the plate. The linear correlation was *extrapolated* ~ 0.8 magnitudes to reach the photographic index of the SN. It is clear, in addition, that in order to derive a B magnitude we need to estimate the (B−V) color of the SN. This estimate will introduce another source of uncertainty.

5. K Corrections

At a redshift of z=0.145, it is important to consider the modification of the flux distribution due to the Doppler effect, and apply the corresponding K corrections to the observed magnitudes, if comparison with SNe observed in the nearby Universe is to be done. We have computed K corrections for the B and V magnitudes of SN 1992ar following the usual prescriptions (see Hamuy et al. 1993, Kim et al. 1996, or Schmidt 1998, for modern discussions), and using spectra of SN 1983V (Clocchiatti et al. 1997), SN 1987M (Filippenko, Porter & Sargent 1990), and SN 1994I (Filippenko et al. 1995, Clocchiatti et al. 1996b, Jeffery et al. 1994). A deeper consideration of K corrections for Type Ic SNe will be given elsewhere (Clocchiatti 1999). It is necessary, however, to give a short discussion here.

Type Ic SNe present a more complex problem than Type Ia SNe, when it comes to applying K corrections. Consider first that, as emphasized by Hamuy et al. (1993), the K-corrections for a SN qualitatively behave as a color. Now, even when Type Ia SNe are not as homogeneous as it was thought just a few years ago, their differences in color evolution do not translate into major differences in the K corrections computed from spectra of different SNe. Even when intrinsic differences in the SNe increase the scatter in the K corrections the results are still reasonably consistent with a unique K correction function for all SNe, at least at redshifts smaller than z$\sim$0.5 (Hamuy et al. 1993). Type Ic SNe, on the other hand, present a much wider range in the speed of the light curve and color evolution. Some of them are extremely fast, like SN 1994I (Richmond et al. 1996), while some others are slow, like SN 1983V (Clocchiatti et al. 1997). These two in particular were considerably faster and slower, respectively, than a typical Type Ia SN. Accordingly, the K corrections for a Type Ic SN are not a unique function of time but critically depend on the speed of the light curve. In Figure 5 we give the K correction in V for a fast and a slow Type Ic SN at z=0.145 as a function of rest frame time since maximum in V, together with the adopted fitting functions. The RMS of the interpolation is 0.06 mag, for fast Ic SNe, and 0.05 for slow Ic SNe. The RMS around the fit for the K correction in B (not given in Fig. 5) is 0.06 mag. We will take these values as a measure of the uncertainty introduced by the K corrections.

In addition, it was necessary to test the possibility that SN 1992ar was a Type Ia SN with a peculiar spectrum. Lacking anything better, K corrections based on typical Type Ia SN spectra were used for this. We took those given by Hamuy et al. (1993), interpolating their values using piece−wise low degree polynomial functions. The adopted corrections are also given in Fig. 5. The RMS around the interpolating function is 0.05 mag in this case.

A different K correction is needed for the B magnitude obtained from the discovery plate, since the sensitivity function of the telescope plus plate system is not matched by a standard filter. We used the sensitivity function computed by Pierce & Jacoby (1995) for the Kitt Peak Schmidt telescope plus a IIa0 plate, under the assumption that it must be similar to that of the Tololo Curtis-Schmidt telescope with the same kind of plate. An additional problem in this case is that this sensitivity function is very blue, and it is difficult to find SNe spectra blue enough to cover this passband. According with the different

SN type and phase we were trying to replicate, we used literature spectra of the Type Ic SN 1994I and the Type Ia SN 1992A, together with their HST spectra (obtained by the SINS collaboration, Jeffery et al. 1994), to compute these K–corrections.

The K correction functions displayed in Fig. 5 illustrate the problem of using the same standard filter in the rest and redshifted frames. Not only are the resulting K corrections function of time, but the time scales of the variations *and their amplitudes*, are similar to those which differentiate one type of SNe light curve from the others, even at the comparatively small redshift of SN 1992ar. This effect emphasizes the importance of observing high redshift SNe in filters that provide a better match to the wavelength range where the light curves used for comparison were observed. These matches can be achieved via the coincidence of effective wavelengths of standard filters for a given redshift (Kim, Goobar & Perlmuter 1996), or the construction of new photometric systems which are the redshifted counterparts of the standard one (Schmidt et al. 1998).

6. The Light Curve

Undilating the time scale using the redshift measured from the emission lines in the nearby galaxies, it is clear that the observed photometry is consistent with that of a SN (see Figure 6). It is clear, also, that the light curve does not correspond to that of a typical Type II plateau event. Finally, it would seem that the confirming spectrum was taken close to maximum light in V.

The strong time variation of the K corrections, however, as illustrated in Fig. 6, implies that obtaining the correct final light curve requires a decision as to which of the functions plotted in Fig. 5 is the correct K correction to apply. The analysis presented in § 2 supports the original identification of SN 1992ar as a Type Ic SN (Hamuy & Phillips 1992). The

SN is, however, surprisingly bright for being a Ic. If $H_0 = 65$ km s^{-1} and $q_0 = 0$, then the distance modulus is 39.28 magnitudes, and the first CCD point implies $M_V = -19.2$ mag, without applying any K correction (which could make the SN brighter), or residual foreground extinction (which *will* make the SN brighter) [30].

According to Hamuy et al. (1996), the absolute V magnitudes of Type Ia SNe range between -19.5 and -18.5, approximately, for the same value of H_0. SN 1992ar therefore compares in brightness with the brightest Type Ia SNe in the Calán/Tololo survey. Other Type Ic SNe observed near maximum are clearly subluminous with respect to typical SNe Ia. SN 1983V (Clocchiatti et al. 1997), a slow Type Ic SN, reached M_V = -18.1 $\pm$0.2, with the uncertainty dominated by the reddening estimate. SN 1994I (Richmond et al. 1996), reached M_V = -18.1 $\pm$0.6, with the big uncertainty due to a large foreground extinction. The fact that SN 1992ar was as much as a magnitude brighter than these two well observed nearby Type Ic SNe raises the question of whether it could have been a Type Ia SN with a peculiar spectrum. We analyze this possibility in the following subsection.

6.1. The case for a Type Ia SN

The spectrum of SN 1992ar, as we discussed before, is more consistent with the spectrum of a Type Ic SNe than with that of a Type Ia. This is so, however, mainly because of the missing Si II λ6355 line. There is at least one example of a Type Ia SN which showed a very weak Si II λ6355 line: the luminous, slow–declining, and spectroscopically peculiar SN 1991T (Filippenko et al. 1992, Phillips et al. 1992). It is important to note that the

[30]We take $H_0 = 65$ km s^{-1} here and throughout the paper in order to compare the absolute brightness of SN 1992ar with those of the other Calán/Tololo SNe given by Hamuy et al. (1996).

peculiar character of the spectrum of SN 1991T, and the weakness of the Si II λ6355 line, were more evident in the pre–maximum stage. Shortly after maximum, the spectrum of SN 1991T became more similar to the typical spectrum of a SN Ia (note that the spectrum of SN 1991T plotted in Fig 2 already shows the Si II λ6355 line). Hence, if SN 1992ar were a 1991T–like event, the spectrum and the photometry points taken shortly before and after it, should most likely correspond to a maximum or premaximum stage.

To test whether SN 1992ar could have been a spectroscopically peculiar Type Ia SN we compared the photometry of Table 1 with typical light curves of Type Ia SN of different speed classes (Hamuy et al. 1996a). We proceeded as follows. We assumed a reasonable phase for the first point (between -6 and 12 days after maximum in V), computed the K correction for each observed phase, corrected the CCD photometry using these K–corrections and fit the resulting data to one of the template SN Ia curves given by Hamuy et al. (1996b). We then computed the RMS of the fit, changed the phase by one day, and iterated the process until finding the phase that provided the minimal RMS. The results of this exercise for the light curves of SN 1992bc, a bright Type Ia SN with a slow decaying light curve similar to that of SN 1991T, and SN 1992A, a fairly typical Type Ia SN, are displayed in Figure 7. Usage of a fast decaying Type Ia light curve, typical of underluminous SNe like SN 1991bg, did not provide a better match to the exponential tail; since it is clear that SN 1992ar was not a low–luminosity event, we do not show those fits.

The fits in Figure 7 show that, for reasonable values of the phase, the light curves of Type Ia SNe provide a poor match to the observed points. In particular, it is not possible to obtain a reasonable fit of either the decay after maximum or the exponential tail with the light curve of a slow decaying Type Ia SN (top panel in Figure 7). The fit is particularly bad if a a negative phase for the spectrum, taken about one day after the first CCD point, is assumed. The absolute magnitude at maximum with this fit would be M_V = -19.08,

($H_0 = 65$ km s^{-1}, $q_0 = 0$), on the dim side for a slow–declining Type Ia SN. Using the light curve of a faster–declining Type Ia SN, like SN 1992A (bottom panel in Figure 7), the decay after maximum is reasonably well matched and the absolute magnitude at maximum results M_V = -19.2, similar to those of the comparable Type Ia SNe in the Calán/Tololo survey. However, the well observed exponential tail is overluminous by $\sim$ 0.6 mag, and allows us to reject this fit.

The only way to obtain a decent fit using the light curve and K corrections of a Type Ia SN is by releasing the requirement that the phase of the first CCD point is “reasonable,” and by assuming that it corresponds to $\sim$17 days after V maximum (see Figure 8). It is at this point that an estimate of the brightness at the time of discovery, based on the discovery plate, could be useful. Using equation 1 plus an estimate of the color of the SN at the time of discovery or the color evolution from the time of the spectrum and the color measured from the spectrum, we obtained the V magnitudes given in Table 4. The color of the SN obtained in this second case is too blue for a SN Ia 12 days after maximum in V. As we see in Figure 8), however, both of the V estimates are consistent with the light curve, given the large uncertainties involved.

Even when the interpretation of SN 1992ar as a typical Type Ia SN caught at late times cannot be ruled out with the sole argument of its light curve, it is questionable on two grounds. First, the maximum of SN 1992ar would have occurred around July 12, 1992, at V$\sim$ 19.1. This implies $M_V = -20.2$ ($H_0 = 65$ km s^{-1} Mpc^{-1}, $q_0 = 0$), more than 0.6 mag brighter than the brightest Type Ia SN in the Calán/Tololo survey. Second, the phase of the spectrum would be $\sim$18 days after V maximum, which is inconsistent with the spectral features seen in Fig. 2. Using a more quantitative approach, spectroscopic dating of the spectrum as described by Riess et al. (1997), indicates that the phase of this spectrum (if it were the spectrum a Type Ia SN) was 6 ± 2 days after V maximum, in gross contradiction with the phase implied by this particular fit of the light curve. These considerations are a strong indication that the photometric evolution and spectral age of SN 1992ar cannot be reasonably matched by any known examples of Type Ia SN light curves and spectra.

6.2. The case for a Type Ic SN

Using the light curves and K–corrections of slow and fast Type Ic SNe, we repeated the procedure of assuming a phase for the first photometric point, computing K–corrections, fitting the light curve for a template, computing of the RMS, and iterating on the phase until the RMS was minimal. As a model of the light curve of a fast Type Ic SN we took SN 1994I (Richmond et al. 1996) and as an example of a slow Type Ic SN we chose the light curve of SN 1993J (Richmond et al. 1994). The latter SN was a transitional Type II, which showed strong He I lines starting ∼20 days after explosion. The second maximum of its light curve and early exponential decay are a good match to the light curves of the slow Type Ic SNe 1983V (Clocchiatti et al. 1997) and 1990B (Clocchiatti et al. 1999). These kind of light curves are probably representative of a photometric group that includes SNe of spectral types Ib, Ic and II transition to Ib. The best fitting light curves and phases are displayed in Figure 9.

It is clear from the figure, that both of the template light curves provide a reasonable match to the CCD photometry within the observational uncertainties and expected intrinsic scattering of each SN subclass, to the point that it is not possible to discard either. The fitting of a fast Ic light curve implies, like in the case of the Ia templates, that maximum occurred several days before the first photometric data were obtained (c.f. Fig. 8). The absolute magnitude implied for maximum would be $M_V \sim -20.2$ mag, again, more than 0.6 mag brighter than the brightest Type Ia SNe in the Calán/Tololo survey. In this case, however, the spectrum is reasonably similar to that of other Type Ic SNe ∼8 days after V maximum (the phase implied by the fit) and thus does not give an argument to discard it.

The fitting of a slow Type Ic SN is also good (see bottom panel in Fig. 9) , and implies an absolute magnitude at maximum of M_V = -19.26 mag, similar to the brightest SNe in the Calán/Tololo survey. It is clear from the figure that the goodness of the fit decreases as the phase increases. This is, however, the expected behavior for stripped–envelope SNe and is consistent with the usual picture of them originating in massive stars which have lost their outer layers. A light curve faster on the tail implies a more rapid decay of the total γ–ray optical depth and is related with a smaller mass–to–energy ratio in the ejecta (see Clocchiatti & Wheeler, 1997, for a simple model).

Again, we can try to decide between this two different interpretation by resorting to brightness estimates based on the discovery plate. From the phases provided by the fits, the B−V color measured from the spectrum, and the assumption of a B−V color evolution similar to those of SN 1994I (Richmond et al. 1996), or SN 1983V (Clocchiatti et al. 1997), we can estimate the color of the SN at the time of the discovery plate for the cases of a fast and slow Type Ic SN, respectively. Another color estimate can be obtained under the assumption that it was similar to that of either SNe *at* the given phase. With these color estimates and equation 1, we can derive its B and hence V, magnitudes. These estimates are given in Table 4. We have these V estimates for each SN type in Fig. 9. As one can see, they are consistent with both the light curve of a slow Type Ic SN and that of a fast one, perhaps slightly better with the latter.

Hence, surprisingly, the photographic plate with the discovery observation of SN 1992ar does not allow us to discriminate between the fast and slow SN Ic templates. Even when the difference between the two interpretations at the time of discovery is about 0.8 mag, the different speed of color and K–correction evolution combine in such a manner so as to make the plate consistent (within the large uncertainties), with either hypothesis.

To summarize, therefore, we can only conclude that, if a phase consistent with that of the spectrum is assumed, the light curve of SN 1992ar is best fit by those of Type Ic SNe. We cannot discern, however, whether it was a fast or a slow one. The rest frame phases, magnitudes, and K corrections implied by the Ic SN fits are given in Table 5. The rest frame B−V color on the date of the spectrum ($\sim$ 4 rest frame days after V maximum for a slow Type Ic SN, and $\sim$ 8 rest frame days after V maximum for a fast Type Ic SN) would have been $\sim$0.62 mag, in both cases, in reasonable agreement with those of other Type Ic SNe at these phases (Clocchiatti et al. 1997, Richmond et al. 1996) when corrections by foreground extinction (to the other SNe) are considered.

7. Discussion and Conclusions

SNe of the Types Ib, Ic, and II-transition to Ib (hereafter referred to as *Transition Type SNe*) display a great degree of heterogeneity both in the appearance of the spectra and in the photometric behavior. Typically understood as stars originally massive which have lost their light element envelopes through episodes of stellar wind and/or mass transfer to interacting binary companions, this diversity has been taken as indicative of a large variety of possible configurations of the progenitor star. Even the three parameter space of two initial stellar masses and their separation, without consideration of the all the possibilities of the complex physics involved, provides many different branches of interacting stellar evolution, and has the potential of providing a variety of combinations of core and envelope at the time of core collapse. Different subsets of these combinations have been proposed to explain SNe of the spectroscopic types Ib, Ic, II−L, and II−n. A handful of these have been studied, with their theoretical light curves and spectra computed, and shown to match the observed light curves and spectra of nearby bright SNe like 1983N, 1993J and 1994I (Woosley et al. 1994); Woosley, Langer & Weaver 1995; Nomoto et al. 1997). All of these recent studies assume the same basic explosion mechanism: The gravitational collapse of an iron core that creates a shock, produces a last episode of stellar nucleosynthesis and disrupts the star, ejecting a relatively small amount of ^{56}Ni ($\sim$0.10 $M_{\odot}$).

The extreme luminosity of SN 1992ar introduces yet another dimension of heterogeneity in this type of explosion. We have collected in Table A, the absolute magnitudes of some of the best studied Transition Type SNe. Although all of them were affected by foreground extinction in various amounts, and this implies a large uncertainty in some cases, it is clear that SN 1992ar's luminosity is unprecedented.

From the spectrum displayed in Fig. 2, the mass to energy ratio of SN 1992ar, as indicated by the square of the expansion velocity, does not appear to be terribly different from that of SN 1987M or 1983V. It is not fair to attach a quantitative estimate to the differences that may exist, however, since the spectra compared correspond to an early epoch. Mass to energy ratios are better represented by the expansion velocities when they reach the asymptotic behavior, typically at the beginning of the radioactive tail. The slope of the light curve, on the other hand, under traditional interpretation of the γ–ray deposition in expanding spherical shells is also related to the mass to energy ratio. According to the simple model of Clocchiatti & Wheeler (1997), for the same mass–density structure and effective γ–ray opacity per unit mass, the difference in slopes some 100 days after maximum indicates that the mass to energy ratio of SN 1992ar was approximately 1.2 times smaller than that of SN 1993J.

We can also estimate the amount of ^{56}Ni powering the light curve of SN 1992ar. Modeling of the light curve of SN 1993J by different groups, at the distance given by recent calibration of Cepheid variables in the parent galaxy (M81), suggests an ejected mass of radioactive ^{56}Ni from 0.073 $M_{\odot}$ (Woosley et al. 1994) up to 0.1 $M_{\odot}$ (Nomoto et al. 1997). Assuming that both the percentage of energy from radioactive decays and the bolometric correction at maximum were similar in SN 1992ar and SN 1993J, the mass of ^{56}Ni ejected in the latter can be obtained using the absolute magnitudes in Table A. The flux in V of SN 1992ar was about 4 times larger than that of SN 1993J, and thus the ^{56}Ni implied for SN 1992ar is between 0.3 $M_{\odot}$ and 0.4 $M_{\odot}$. In the case of a fast Type Ic SN light curve fit, we can compare again with SN 1994I. Iwamoto et al. (1994) estimated an ejected ^{56}Ni mass of $0.07^{+0.035}_{-0.025}$ $M_{\odot}$. According with Table A, the flux in V of SN 1992ar was approximately 7 times larger than that of SN 1994I so a scaling of Iwamoto's estimate will put the ^{56}Ni mass of SN 1992ar at $\sim$0.5 $^{+0.25}_{-0.18}$. Both of these estimates indicate that the ^{56}Ni mass ejected by SN 1992ar should have been comparable to that produced by a fairly bright Type Ia SN (Arnett 1996).

A subset of Transition Type SNe, including the slow Type Ic events, follows a similar photometric evolution even though they display a variety of spectra at maximum. SN 1993J, which is a good example of the objects in this photometric group, is well understood in terms of a "traditional" core collapse explosion. Could one of these explosions produce as much ^{56}Ni as required by the slow Type Ic SN fit to SN 1992ar? Or, alternatively, could a core collapse explosion in a $\sim 2M_{\odot}$ C+O star like the one used by Iwamoto et al. (1994) to match the light curve of SN 1994I, produce half a solar mass of ^{56}Ni? The other option is to conclude that there are some stripped envelope SNe which, contrary to conventional wisdom, do explode via a thermonuclear explosions (Branch, Nomoto & Filippenko 1991). Whether a thermonuclear explosion could give a Ic spectrum together with the fast decline after maximum and slow decline on the tail of a slow Type Ic SN, *or* the fast light curve of a fast Type Ic SN, is a question that merits further study.

The existence of luminous Type Ic SNe such as SN 1992ar has important implications for the the high–redshift SNe searches currently under way with the aim of measuring the cosmological parameters of the universe (Perlmutter et al. 1998, Schmidt et al. 1998) because it exemplifies the problem of sample contamination. SN 1992ar shows that there are SNe which are as bright as a Type Ia SN and have a similar light curve near maximum light, but have different intrinsic colors, different color evolution, and do not follow the Light Curve Shape–Luminosity relation used to calibrate the intrinsic luminosity of a Type Ia SN.

One of the earliest and clearest indications that SN 1992ar was a peculiar event was given by its spectrum, which did not display the SiII λ6355 line. If SN 1992ar had been at a redshift larger than $\sim$0.50, however, this line would have been Doppler shifted to $\sim$9200 Å, and the brightness at maximum would have been around R$\sim$23 mag. This, together with the poorer sensitivity and typical fringing of most spectrographs in the far red, would have made it very difficult for the observers to distinguish on spectroscopic grounds such a SN from a typical SN Ia (See Riess et al. 1998, for an example of this problem). The light curve (which almost surely would have had worse signal-to-noise ratio and shorter time baseline than those of SN 1992ar) would have probably been acceptably fitted with a typical Type Ia like curve, using parameters similar to those of the bottom panel in Fig. 7. Note that this fit implies a phase of $\sim$ 7 days after V maximum for the spectrum, in good agreement with the spectroscopic age derived by the method of Riess et al. (1997) for the spectrum of SN 1992ar. Using the K corrections for Type Ia SN, the rest frame color at the time of the spectrum implied by this fit ($\sim$7 days after V maximum) is B$-$V= 0.6 mag, somewhat red in comparison with a typical Ia SN $\sim$ 10 days after B maximum. This red color, however, would have been interpreted as indicative of foreground extinction, and the intrinsic brightness of SN 1992ar would have been increased accordingly. In the end, the luminosity distance derived from this object (if it were assumed to be a Type Ia SN) would have been too short. The possibility exists, therefore, depending on the signal-to-noise ratio of the observational sets obtained for a particular object, that the samples of SNe with z $\gtrsim$ 0.5 can be contaminated by bright Ic SNe like 1992ar.

With current detectors and telescopes, which make detection of the SiII λ6355 line difficult for SNe with z $\gtrsim$ 0.5, the most reliable means of eliminating bright Type Ic SNe from the high z SNe samples SNe will be: (1) To obtain high S/N ratio spectra in the visual and red regions in order to detect the typically much weaker SiII lines at 4130 and 5051 Å (note that the line SiII λ5972 could appear merged with NaI D, so its diagnostic power is limited), and the SII lines at 5468, 5612 and 5654 Å, which have never been claimed to be present in the spectrum of Type Ic SNe, *and*, (2) to obtain well time sampled two color light curves with good signal-to-noise ratio including at least a pre–maximum point and, especially, a couple of good points, with photometric uncertainty smaller than ∼0.05 mag on the early exponential tail, between 40 and 60 days after maximum light.

A good S/N ratio data set for a high z SN would allow to apply the following criteria. If a SN has a red color, does not show evidence for SiII λ4130, SiII λ5051, SII λ5468, SII λ5612, and SII λ5654 lines, displays a maximum noticeably narrower than that of a Type Ia SN, *or* a light curve which remains brighter than the Type Ia SNe light curve templates on the early exponential tail, it should be suspect of being a Type Ic SN and excluded from the samples.

How could these luminous Type Ic SNe affect the high z Hubble diagrams if not removed from the samples? According to the current, scarce, database, and opposite to what Type Ia SNe display, the shapes of light curves of Transition Type SNe do not seem to correlate with their intrinsic brightness. As we have shown, the same type of light curves fit SNe with very different intrinsic brightness. In the cases of a slow Type Ic SN fit for SN 1992ar this means $M_V = -17.4$ (SN 1983N), and $M_V = -19.2$ (SN 1992ar), while in the case of a fast Type Ic SN fit for SN 1992ar it means $M_V = -18.1$ (SN 1994I), and $M_V = -20.2$ (SN 1992ar). It could well be that the process which determines the amount of ^{56}Ni ejected in core–collapse explosions is intrinsically chaotic and bears no relation to the mass to energy ratio of the explosions, responsible for the light curve shapes. It would appear, in principle, that the main effect of not removing objects like SN 1992ar from the high z Type Ia SNe samples will be an increase in the scatter of the final Hubble Diagrams.

On the other hand, systematic shifts may enter through Malmquist bias. If most of the Type Ic which go unchecked and are included in the samples are as bright as SN 1992ar (i.e. slightly brighter than a typical Type Ia SN), then the sample of distant SNe will be biased in the sense of appearing brighter than they should. The result of this will be that the distances estimated will be shorter than they are, and consistent with a positive deceleration parameter q_0, or alternatively, with higher values of Ω_M and lower values of Ω_Λ.

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A. A note on SN 1998bw in ESO 184-G82

While this paper was in the final stages of writing and submission the first results on SN 1998bw became available (Saddler et al. 1998, Kulkarni et al., 1998, Galama et al. 1998). Although a detailed comparison of SNe 1998bw and 1992ar is beyond the scope of the present paper, a note cross linking them is necessary. SN 1998bw was discovered well within the error box of GRB 980425 and there is compelling evidence that it was associated with the burst. SN 1998bw displayed peculiarities in its light curve and spectra, with a very fast rise to maximum (Woosley, Eastman & Schmidt 1999), and photospheric expansion velocities of $\sim$28,000 km s^{-1} ten days after explosion (Iwamoto et al. 1998). SN 1998bw was also recognized as a very bright event. At an absolute magnitude of $M_V = -19.35 \pm 0.05$ (Galama et al. 1998), however, it could have been dimmer than SN 1992ar. If the two events correspond to core–collapse explosions, they show very clearly that this mechanism does not result in a correlation between ^{56}Ni mass ejection and mass to energy ratio in the ejecta.

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Fig. 1.— Chart of the region of SN 1992ar. The sequence of local standard stars used to calibrate the brightness of the SN is labeled by numbers positioned towards the NE of the referenced stars. Note that objects number 5 and 9 are not stars but galaxies. The three galaxies nearby the SN are labeled by letters. The position of the SN is given by a white square dot towards the SE of these group of galaxies.

Fig. 2.— Comparison of the spectrum of SN 1992ar with those of the Type Ia SN 1989B (Wells et al. 1994) and 1991T (Phillips et al. 1992). The wavelength scales of the spectra have been corrected for the redshift of the parent galaxies. The phase of the spectrum of SN 1992ar corresponds to the slow Type Ic light curve fit discussed in § 6.2. Identification of the main features, labeled by lower case letters above the spectrum of SN 1991T are: (a) CaII H & K, (b) FeII "λ4274", (c) FeII "λ4555", (d) FeII λ5018, (e) FeII λ5169, (f) NaI D / SiII "λ5972," (g) SiII "λ6355." Secondary weaker features which could be used to distinguish Type Ia from Type Ic SNe are labeled with capital letters, as follows: (A) SiII λ4130, (B) SiII λ5051, (C) SII "λ5468," and, (D) SII "$\lambda\lambda$5612," "5654."

Fig. 3.— Comparison of the spectrum of SN 1992ar with those of the Type Ic SN 1983V (Clocchiatti et al. 1997) and 1987M (Filippenko, Porter, & Sargent 1990). The wavelength scales of the spectra have been corrected for the redshift of the parent galaxies. The phase of the spectrum of SN 1992ar corresponds to the slow Type Ic light curve fit discussed in § 6.2. Identification of the main features, labeled by letters above the spectrum of SN 1983V are: (a) CaII H & K, (b) FeII "λ4274", (c) FeII "λ4555", (d) FeII λ5018, (e) FeII λ5169, (f) NaI D, (g) SiII "λ6355."

Fig. 4.— Spectra of the three galaxies nearby SN 1992ar. The wavelength scale of the spectra are given in the observer's frame (i.e. not corrected by redshift of the parent galaxies). The forbidden emission lines are marked by vertical lines and labeled on the top spectrum (Galaxy A). They are, in increasing order of wavelength, [O II] $\lambda\lambda$3726,3729; [O III] $\lambda\lambda$4959,5007;

and [NI] λ5198. The hydrogen recombination lines Hδ, Hγ, and Hβ, with the latter seen in emission, have been also marked on this top spectrum. For clarity of the plot, the hydrogen recombination lines Hϵ, Hξ, and the CaII H&K lines, all seen in absorption, have been marked on the bottom spectrum (Galaxy C).

Fig. 5.— The K–corrections in V for Type Ic slow, Type Ic fast, and Ia SNe at z= 0.145. The vertical scale of both panels is the same to facilitate comparisons.

Fig. 6.— Observed raw photometry of SN 1992ar (with no K corrections applied), compared with the different final light curves that result when different K–correction functions are assumed. Solid circles, joined by solid line, show the raw photometry ($V_{0.145}$). Open circles joined by a dotted line, correspond to $V_{0.145}$ minus the K–correction of a slow Type Ic SN. Open squares joined by a short dashed line correspond to $V_{0.145}$ minus the K–correction of a fast Type Ic SN. Open triangles joined by a long dashed line correspond to $V_{0.145}$ minus the K–correction of a Type Ia SN. A phase of 3 days after V maximum was assumed for all light curves. The arrow marks the time position of the spectrum.

Fig. 7.— Type Ia SNe light curves compared with the CCD photometry of SN 1992ar. The top panel shows the fitting of a slow decaying luminous Type Ia SN, illustrated in this case by SN 1992bc (Hamuy et al. 1996). The RMS of the fit is minimized when a phase of 3 days after V maximum is assumed for the first CCD observation. The bottom panel shows the fitting of a more typical Type Ia SN, exemplified by SN 1992A. The RMS of the fit is minimized when a phase of 6 days after V maximum is assumed for the first CCD point.

Fig. 8.— Fitting of the light curve of SN 1992A to the observed photometry of SN 1992ar assuming that the phase of the first CCD observation is $\sim$17 days after maximum light in V. The arrow marks the time position of the spectrum. The open squares with large error bars are the rest frame V magnitudes estimated from the plate, using two different estimates of

the color of the SN (see Table 4).

Fig. 9.— Fitting of Type Ic SNe light curves to the observed photometry of SN 1992ar. The top panel shows the fit of a fast Type Ic SN, exemplified by SN 1994I (Richmond et al. 1996). The arrow marks the time position of the spectrum. The bottom panel shows the fitting of SN 1993J, whose light curve is a good match to those of slow Type Ic SN. The arrow marks the time position of the spectrum. In both panels, the open square with a large error bar shows the rest frame V magnitude estimated from the discovery plate (see Table 4).

Table 1: Photometric Observations of SN 1992ar

Date[a]	V	B	R	Source
35.93	20.11 ± 0.04	—	—	CTIO 0.91m + CCD — R. Avilés/C. Smith
36.78	—	21.05 ± 0.20	—	B−V=0.85 (spectrum) and V=20.20.
40.80	—	21.47 ± 0.19	—	CTIO 0.91m + CCD — E.P. Rubenstein
40.81	20.54 ± 0.06	—	—	CTIO 0.91m + CCD — E.P. Rubenstein
47.71	21.22 ± 0.12	—	—	CTIO 0.91m + CCD — R. Avilés
67.55	21.91 ± 0.05	—	21.14 ± 0.07	ESO 3.6m + EFOSC1 — E. Cappellaro
98.78	—	—	22.13 ± 0.07	ESO/MPI 2.2m + EFOSC2 — M. Della Valle
98.79	22.31 ± 0.07	—	—	ESO/MPI 2.2m + EFOSC2 — M. Della Valle
99.65	22.30 ± 0.08	—	—	ESO/NTT + EMMI — M. Della Valle
156.54	23.22 ± 0.15	—	—	ESO 3.6m + EFOSC1 — M. Della Valle

[a] JD−2448800

Table 2: Final Epoch Images of SN 1992ar Region

Date	Phase	Filter	Telescope and Instrument	Observer
1993, Sep 9 - 6:35	409	B	CTIO 4.0m – Cass CCD Camera	M. Navarrete
1993, Nov 11 - 3:53	472	V	CTIO 4.0m – Cass CCD Camera	R. Avilés
1996, Dec 15 - 2:21	1602	R	ESO 2.2m – EFOSC 2	C. Zanin

Table 3: Local Standard Sequence

ID	V	B	B−V	R
92ar-1	16.15 ± 0.02	16.79 ± 0.02	0.65 ± 0.03	15.67 ± 0.04
92ar-2	18.48 ± 0.02	19.37 ± 0.03	0.89 ± 0.03	17.83 ± 0.05
92ar-3	16.72 ± 0.02	17.85 ± 0.03	1.14 ± 0.03	15.87 ± 0.07
92ar-4	17.61 ± 0.02	19.05 ± 0.03	1.44 ± 0.03	16.42 ± 0.09
92ar-5	17.53 ± 0.02	18.81 ± 0.03	1.28 ± 0.03	—
92ar-6	17.05 ± 0.02	17.71 ± 0.03	0.67 ± 0.03	16.57 ± 0.04
92ar-7	17.99 ± 0.02	18.61 ± 0.03	0.62 ± 0.03	—
92ar-8	20.73 ± 0.05	21.60 ± 0.12	0.87 ± 0.13	19.95 ± 0.06
92ar-9	18.31 ± 0.02	19.70 ± 0.03	1.39 ± 0.03	—
92ar-11	20.04 ± 0.03	21.41 ± 0.09	1.38 ± 0.10	18.70 ± 0.08
92ar-12	19.97 ± 0.03	20.23 ± 0.05	0.26 ± 0.06	20.03 ± 0.03
92ar-13	20.22 ± 0.03	21.66 ± 0.11	1.44 ± 0.11	18.97 ± 0.09

Table 4: Rest Frame Magnitudes at Discovery

Type	Ph.[a]	K_{IIaO}	K_B	K_V	$B\text{-}V_{0.145}$	$B\text{-}V_0$	B_0	V_0
Ia[b]	12	0.55	0.38±0.1	0.03±0.05	0.80±0.22	0.45±0.20	19.83±0.26	19.38±0.34
Ia[c]	12	0.55	0.38±0.1	0.03±0.05	0.40±0.20	0.05±0.22	19.91±0.26	19.86±0.34
Ic Slow[b]	-1.5	0.43	0.16±0.1	-0.05±0.05	0.38±0.22	0.20±0.20	20.07±0.26	19.90±0.34
Ic Slow[c]	-1.5	0.43	0.16±0.1	-0.05±0.05	0.56±0.20	0.35±0.22	20.04±0.26	19.69±0.34
Ic Fast[b]	2.5	0.59	0.25±0.1	0.03±0.05	0.77±0.22	0.55±0.20	19.79±0.26	19.24±0.34
Ic Fast[c]	2.5	0.59	0.25±0.1	0.03±0.05	0.64±0.20	0.42±0.22	19.81±0.26	19.39±0.34

[a]Phase in rest frame days after V maximum.

[b]Rest frame color at discovery assumed.

[c]Rest frame color at discovery extrapolated from the spectrum.

Table 5: Rest Frame Light Curve of SN 1992ar (Ic fits)

	Slow Type Ic SN Fit			Fast Type Ic SN Fit		
Date[a]	Phase	$K_{V,Slow}$	V_{Slow}	Phase	$K_{V,Fast}$	V_{Fast}
35.93	3.00	0.04	20.07 ± 0.09	7.000	0.11	20.00 ± 0.08
40.81	7.26	0.12	20.43 ± 0.11	11.26	0.17	20.37 ± 0.09
47.71	13.29	0.20	21.02 ± 0.14	17.29	0.13	21.09 ± 0.14
67.55	30.61	0.28	21.63 ± 0.10	34.61	-0.21	22.12 ± 0.09
98.79	57.90	0.10	22.22 ± 0.11	61.90	-0.29	22.60 ± 0.10
99.65	58.65	0.10	22.20 ± 0.12	62.65	-0.29	22.59 ± 0.11
156.54	108.33	-0.05	23.27 ± 0.17	112.33	-0.43	23.65 ± 0.17

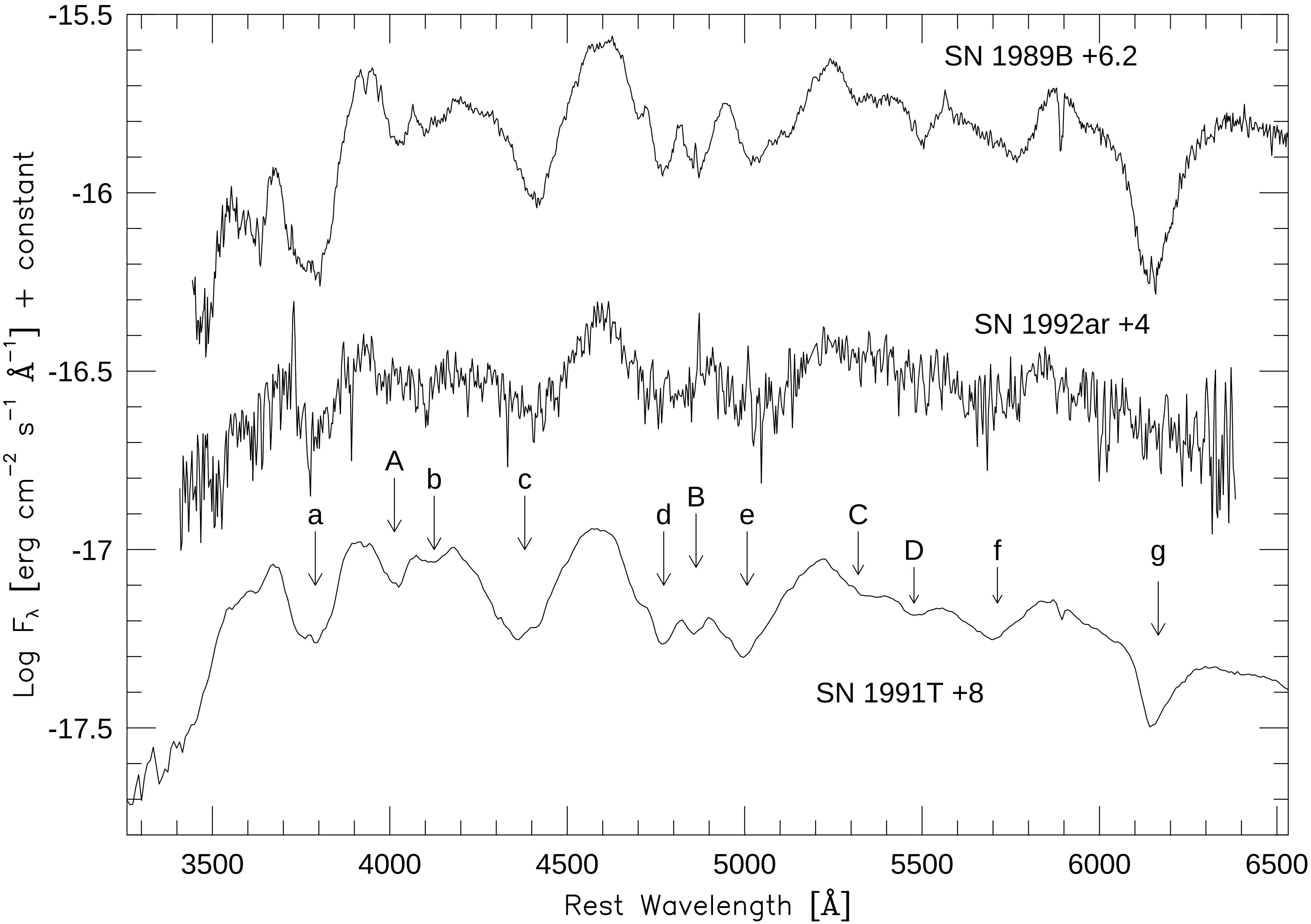
[a]JD−2448800

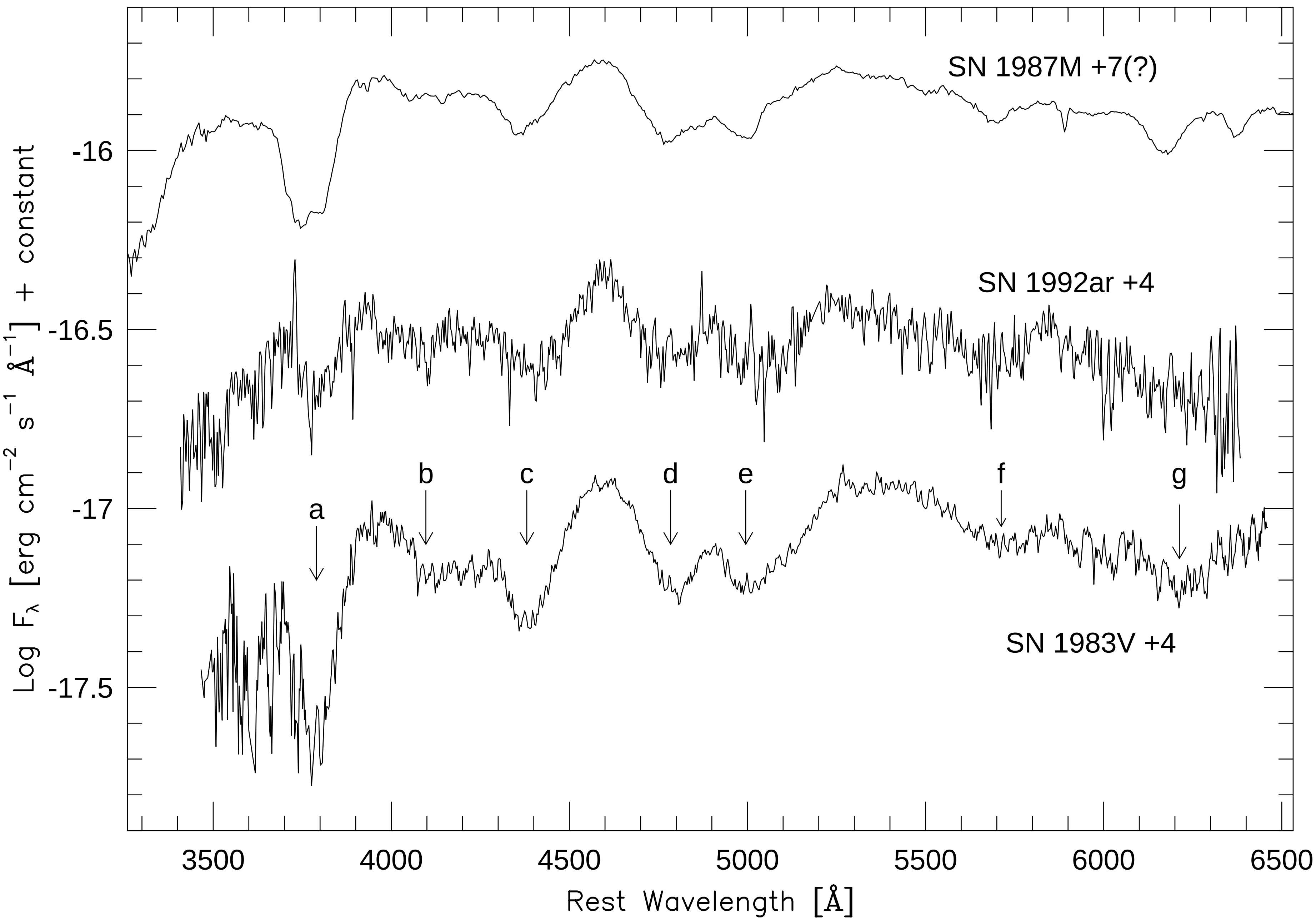
Table 6: M_V of Transition Type SNe

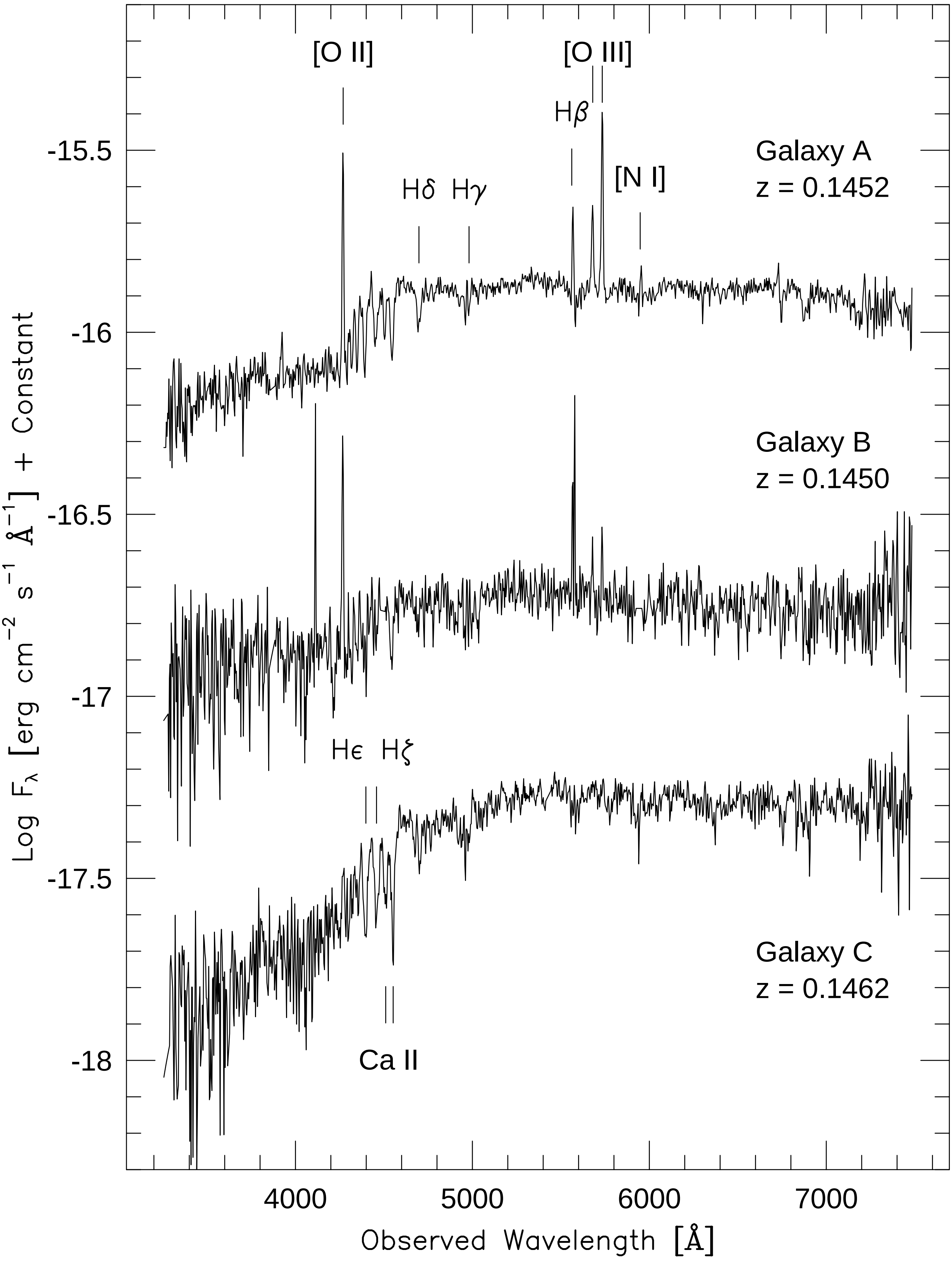
SN	M_V	Source
1983N	-17.4 ± 0.2	Clocchiatti et al. (1996)
1983V	-18.1 ± 0.2	Clocchiatti et al. (1997)
1992ar	-19.2 ± 0.2	This paper[a]
1992ar	-20.2 ± 0.2	This paper[b]
1993J	-17.7 ± 0.1	Table 5 in Clocchiatti et al. (1997)
1994I	-18.1 ± 0.6	Richmond et al. (1996)

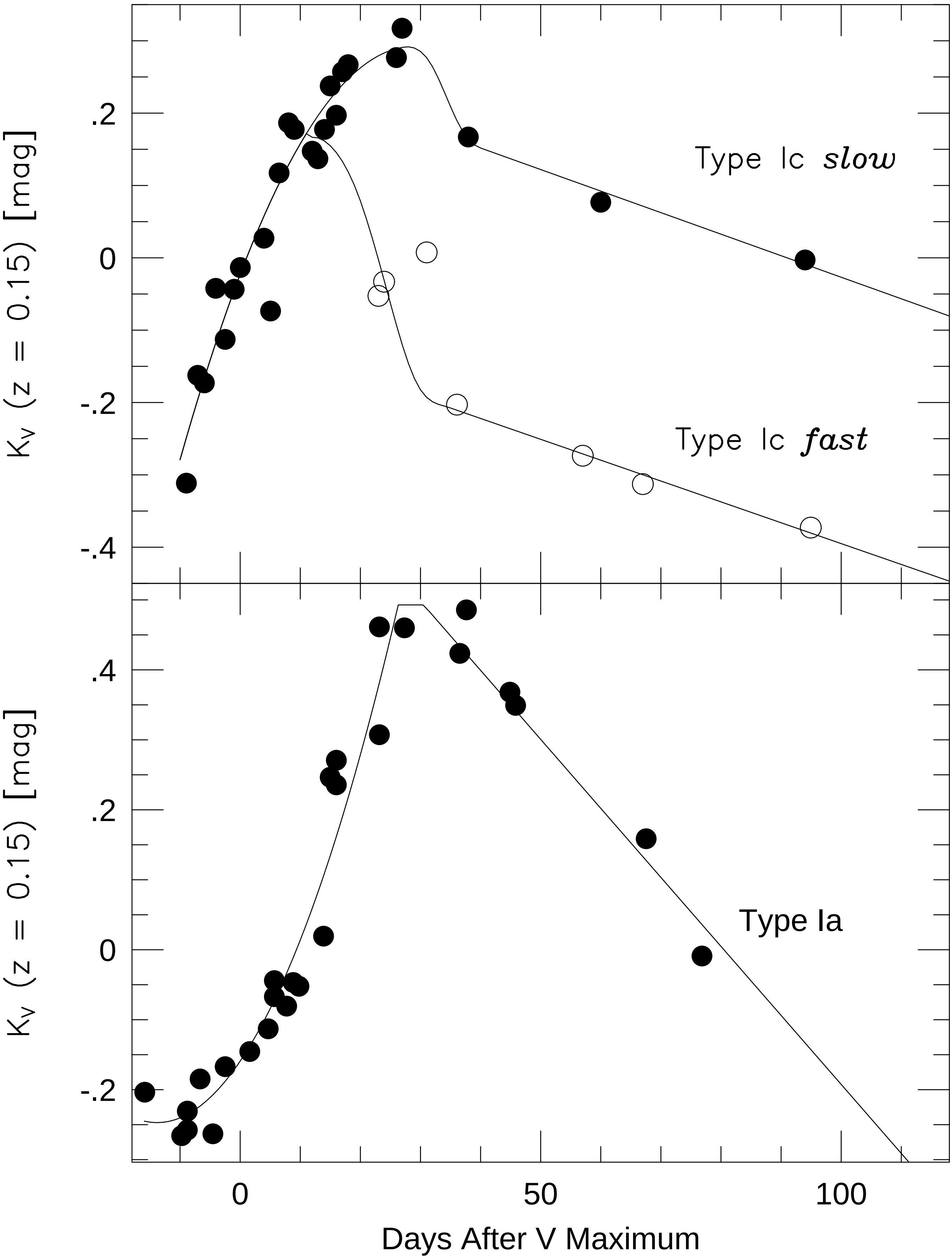
[a]If it was a Slow Type Ic SN. Uncertainty estimated from the template fitting.

[b]If it was a Fast Type Ic SN. Uncertainty estimated from the template fitting.

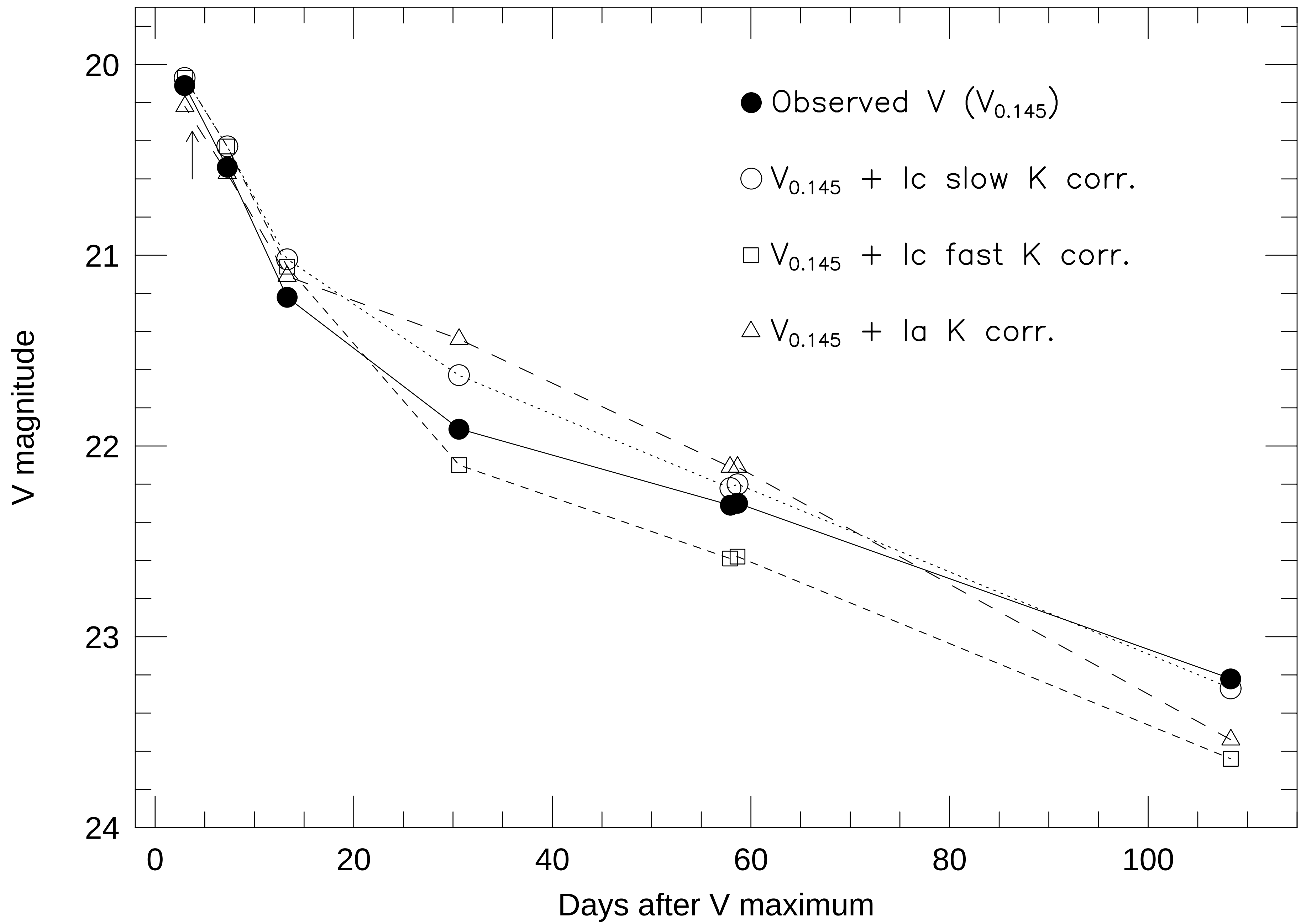

SN 1989B +6.2
SN 1992ar +4
SN 1991T +8
a
A
b
c
d
B
e
C
D
f
g
-15.5
-16
-16.5
-17
-17.5
3500
4000
4500
5000
5500
6000
6500
Log F_λ [erg cm^{-2} s^{-1} Å^{-1}] + constant
Rest Wavelength [Å]


SN 1987M +7(?)
SN 1992ar +4
SN 1983V +4
a
b
c
d
e
f
g
-16
-16.5
-17
-17.5
Log F_λ [erg cm^{-2} s^{-1} Å^{-1}] + constant
3500
4000
4500
5000
5500
6000
6500
Rest Wavelength [Å]

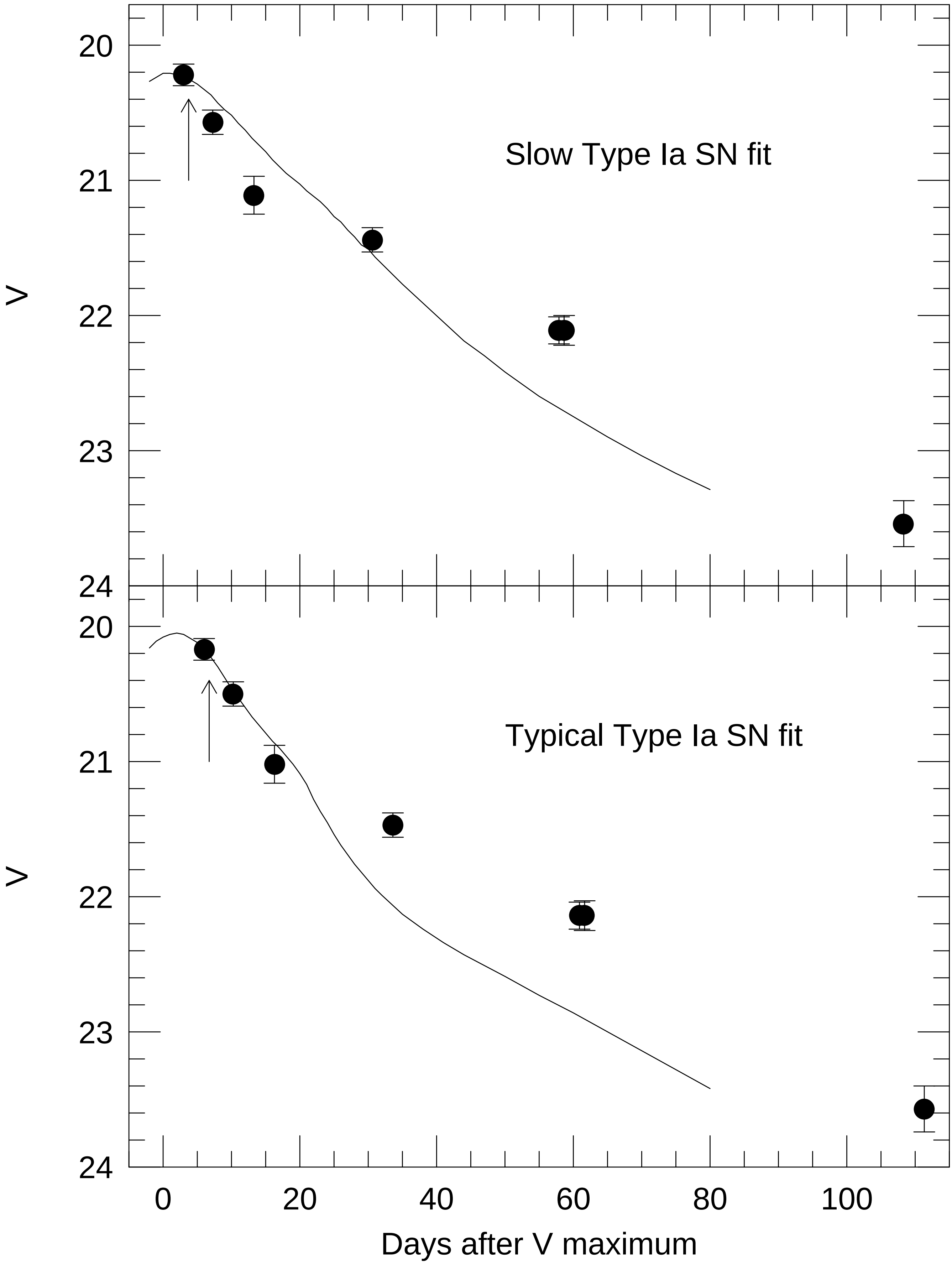

[O II]
[O III]
Hβ
Hδ
Hγ
[N I]
Galaxy A
z = 0.1452
Galaxy B
z = 0.1450
Hϵ
Hζ
Galaxy C
z = 0.1462
Ca II
-15.5
-16
-16.5
-17
-17.5
-18
4000
5000
6000
7000
Observed Wavelength [Å]
Log F_λ [erg cm^-2 s^-1 Å^-1] + Constant



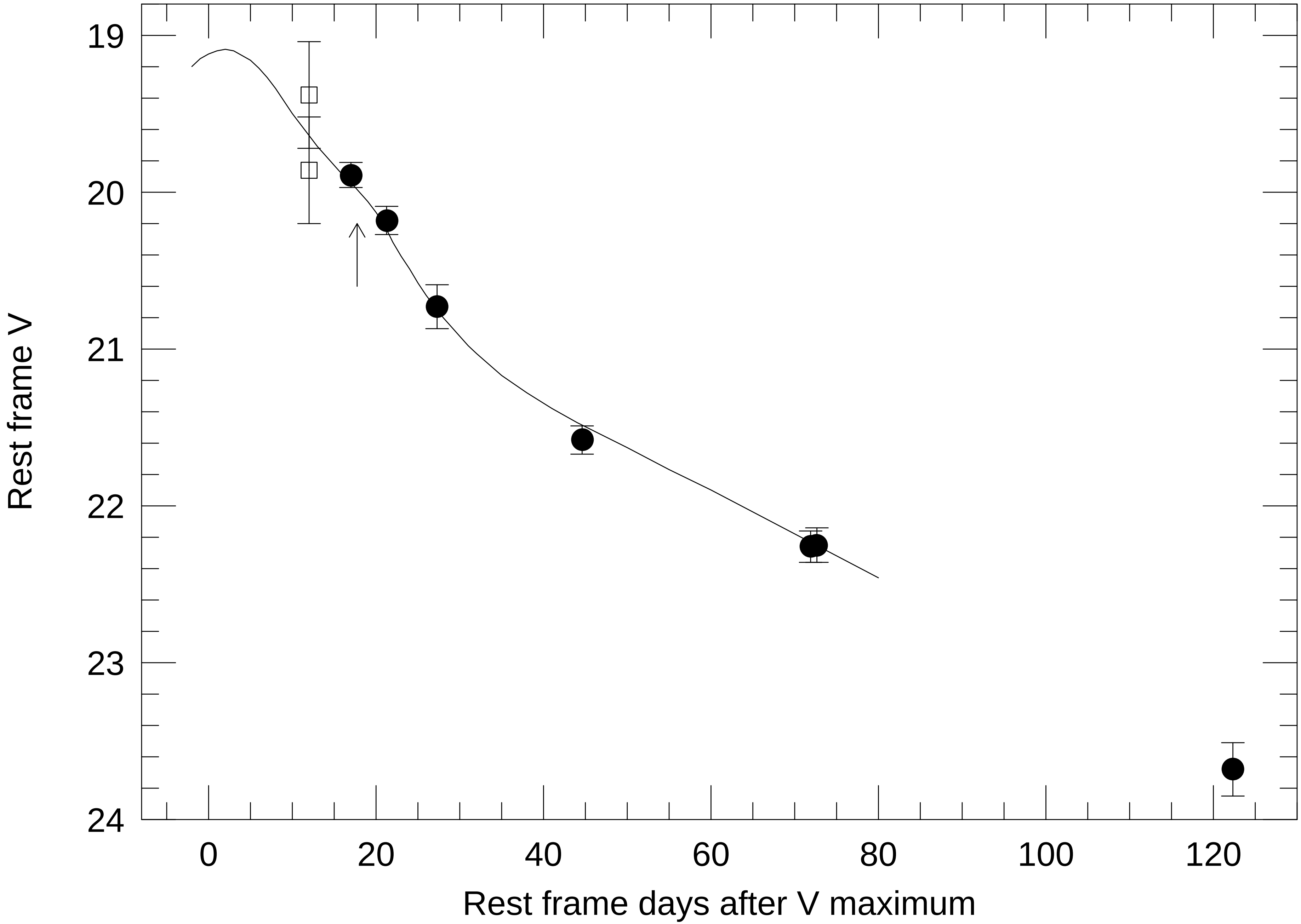
Type Ic slow
Type Ic fast
Type Ia
K_V (z = 0.15) [mag]
.2
0
-.2
-.4
.4
0
50
100
Days After V Maximum

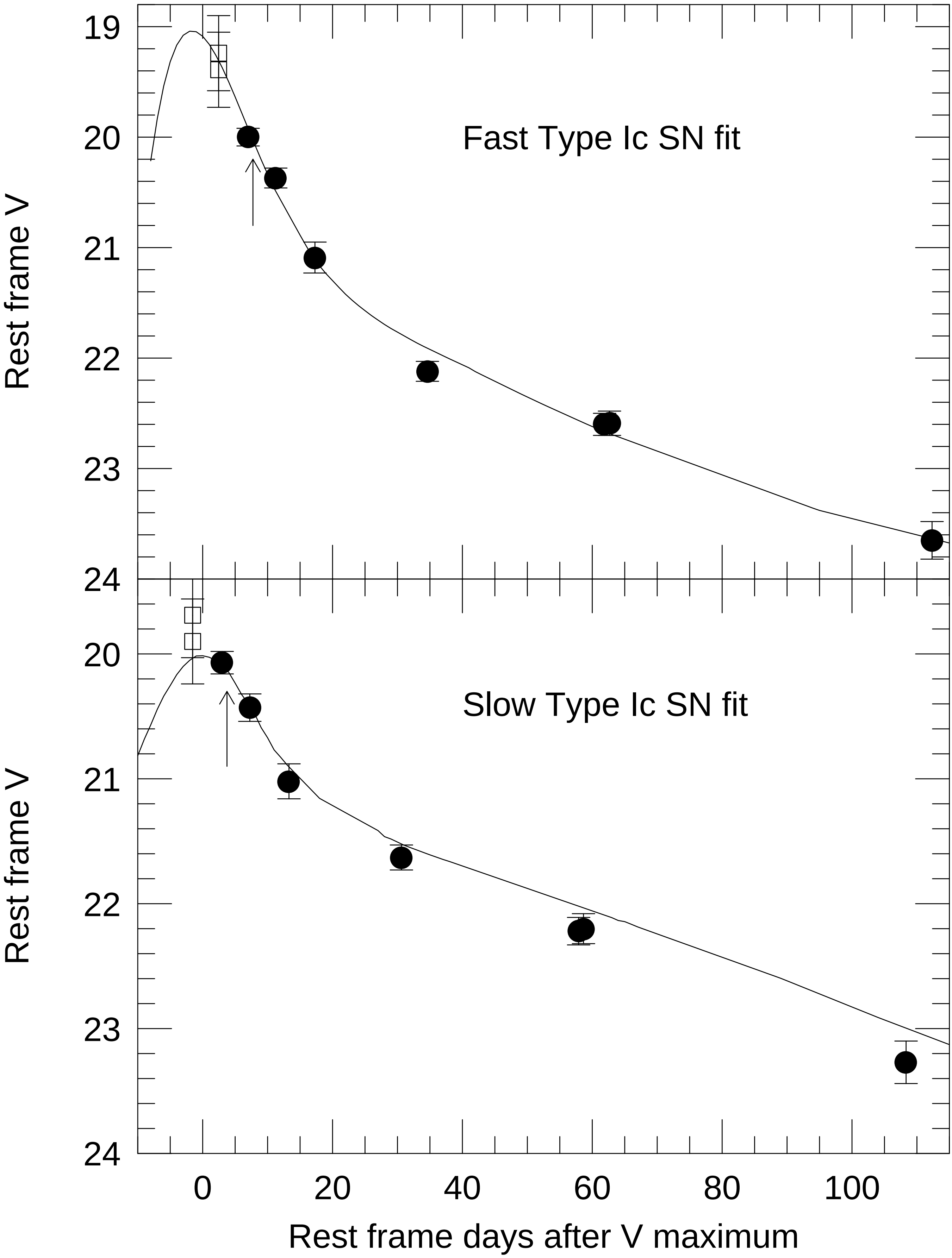


V magnitude
20
21
22
23
24
0
20
40
60
80
100
Days after V maximum
Observed V ($V_{0.145}$)
$V_{0.145}$ + Ic slow K corr.
$V_{0.145}$ + Ic fast K corr.
$V_{0.145}$ + Ia K corr.



Slow Type Ia SN fit
Typical Type Ia SN fit
V
20
21
22
23
24
0
20
40
60
80
100
Days after V maximum


Rest frame V
19
20
21
22
23
24
0
20
40
60
80
100
120
Rest frame days after V maximum



Fast Type Ic SN fit
Slow Type Ic SN fit
Rest frame V
Rest frame V
19
20
21
22
23
24
20
21
22
23
24
0
20
40
60
80
100
Rest frame days after V maximum